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# A Workshop to Identify Approaches for Achieving Priority Research for Eastern Bering Sea Snow Crab Biology and Fishery Management

**by**

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# Symbols and Abbreviations

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**Weights and measures (metric)**

| | |
|---|---|
| centimeter | cm |
| deciliter | dL |
| gram | g |
| hectare | ha |
| kilogram | kg |
| kilometer | km |
| liter | L |
| meter | m |
| milliliter | mL |
| millimeter | mm |

**Weights and measures (English)**

| | |
|---|---|
| cubic feet per second | $ft^3/s$ |
| foot | ft |
| gallon | gal |
| inch | in |
| mile | mi |
| nautical mile | nmi |
| ounce | oz |
| pound | lb |
| quart | qt |
| yard | yd |

**Time and temperature**

| | |
|---|---|
| day | d |
| degrees Celsius | °C |
| degrees Fahrenheit | °F |
| degrees kelvin | K |
| hour | h |
| minute | min |
| second | s |

**Physics and chemistry**

| | |
|---|---|
| all atomic symbols | |
| alternating current | AC |
| ampere | A |
| calorie | cal |
| direct current | DC |
| hertz | Hz |
| horsepower | hp |
| hydrogen ion activity (negative log of) | pH |
| parts per million | ppm |
| parts per thousand | ppt, ‰ |
| volts | V |
| watts | W |

**General**

| | |
|---|---|
| Alaska Administrative Code | AAC |
| all commonly accepted abbreviations | e.g., Mr., Mrs., AM, PM, etc. |
| all commonly accepted professional titles | e.g., Dr., Ph.D., R.N., etc. |
| at | @ |
| compass directions: | |
| east | E |
| north | N |
| south | S |
| west | W |
| copyright | © |
| corporate suffixes: | |
| Company | Co. |
| Corporation | Corp. |
| Incorporated | Inc. |
| Limited | Ltd. |
| District of Columbia | D.C. |
| et alii (and others) | et al. |
| et cetera (and so forth) | etc. |
| exempli gratia (for example) | e.g. |
| Federal Information Code | FIC |
| id est (that is) | i.e. |
| latitude or longitude | lat or long |
| monetary symbols (U.S.) | $, ¢ |
| months (tables and figures): first three letters | Jan,...,Dec |
| registered trademark | ® |
| trademark | ™ |
| United States (adjective) | U.S. |
| United States of America (noun) | USA |
| U.S.C. | United States Code |
| U.S. state | use two-letter abbreviations (e.g., AK, WA) |

**Mathematics, statistics**

| | |
|---|---|
| *all standard mathematical signs, symbols and abbreviations* | |
| alternate hypothesis | $H_A$ |
| base of natural logarithm | *e* |
| catch per unit effort | CPUE |
| coefficient of variation | CV |
| common test statistics | (F, t, $\chi^2$, etc.) |
| confidence interval | CI |
| correlation coefficient (multiple) | R |
| correlation coefficient (simple) | r |
| covariance | cov |
| degree (angular ) | ° |
| degrees of freedom | df |
| expected value | *E* |
| greater than | > |
| greater than or equal to | ≥ |
| harvest per unit effort | HPUE |
| less than | < |
| less than or equal to | ≤ |
| logarithm (natural) | ln |
| logarithm (base 10) | log |
| logarithm (specify base) | $log_2$, etc. |
| minute (angular) | ' |
| not significant | NS |
| null hypothesis | $H_O$ |
| percent | % |
| probability | P |
| probability of a type I error (rejection of the null hypothesis when true) | α |
| probability of a type II error (acceptance of the null hypothesis when false) | β |
| second (angular) | " |
| standard deviation | SD |
| standard error | SE |
| variance | |
| population | Var |
| sample | var |

*SPECIAL PUBLICATION NO. 14-07*

# A WORKSHOP TO IDENTIFY APPROACHES FOR ACHIEVING PRIORITY RESEARCH FOR EASTERN BERING SEA SNOW CRAB STOCK BIOLOGY AND FISHERY MANAGEMENT

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# ABSTRACT

A symposium and workshop held 22–24 February 2011 in Seattle, WA, brought together international and regional experts in the biology, ecology, stock assessment, and fisheries management of snow crab *Chionoecetes opilio*. The symposium included presentations briefly summarizing the current status of knowledge on snow crab, methods and issues relevant to stock assessment, fishery management, ongoing data collection programs in the eastern Bering Sea (EBS), and current research on EBS snow crab. The workshop consisted of open discussion focused on the following goals: 1) identify key uncertainties, poorly estimated stock productivity parameters, and gaps in the understanding of population processes for snow crab in the eastern Bering Sea (EBS), especially relative to the information needed for management of the EBS commercial fishery; 2) establish priority research objectives for addressing the identified uncertainties, poorly estimated parameters, and gaps in understanding; and 3) suggest approaches for achieving those research objectives. Seven research objectives for EBS snow crab were identified as priorities for providing critically needed information: characterize the spatial-temporal distribution of males relative to mating and reproductive output, estimate variability in female reproductive potential, improve understanding of larval ecology, estimate growth throughout ontogeny, estimate natural mortality, estimate total fishing-induced mortality, and improve accuracy and precision of survey-based stock abundance estimates. Analyses using archived data sets, modifications to current data collection programs, and new research initiatives were suggested to address those research objectives.



Keywords: *Chionoecetes opilio*, crab, assessment, biology, distribution, fishing mortality, fisheries management, growth, life history, mating, movement, natural mortality, reproduction, research priorities, snow crab, workshop


# INTRODUCTION

The eastern Bering Sea (EBS) snow crab *Chionoecetes opilio* stock supports the largest commercial crab fishery in Alaska; annual landings exceeded 300 million pounds (136,078 metric tons) in 1991 and 1992, and annual exvessel value exceeded $150 million during 1991–1995 (Bowers et al. 2011). Moreover, during the 1990s, the EBS snow crab fishery contributed significantly to the total annual landings and value of commercial crab fisheries in the U.S., accounting for almost one-half of the total weight of landings and over one-third of the total value of landings of all U.S. commercial crab fisheries in certain years (Figure 1). Bowers et al. (2011) and Turnock and Rugolo (2010) reported details on the history of the fishery and trends in stock abundance, which are reviewed here briefly. Snow crab were commercially harvested from the EBS by foreign fleets from the 1960s until 1980, and domestic landings of EBS snow crab began in 1977. Estimated mature stock biomass and landings peaked in the 1990s. However, in 1999, the stock spawning biomass was estimated to have fallen below the minimum stock size threshold (MSST) established in the Fishery Management Plan (FMP) for the Commercial King and Tanner Crab Fisheries in the Bering Sea/Aleutian Islands (NPFMC 1998), resulting in a federal overfished declaration for the stock, development of a stock rebuilding plan (NPFMC 2000), and significantly reduced harvest levels in subsequent years. In 2009, the stock was determined to have failed to rebuild according to the 10-year schedule specified by the rebuilding plan (NPFMC 2009), and the fishery continued to be managed under a stock rebuilding plan into 2011.

Snow crab are widely distributed on the EBS continental shelf and commonly occur at depths of 50–150 m. The distribution of effort during the winter commercial fishery is limited largely to the areas near the continental shelf edge at depths of 100–150 m and in areas free of sea ice coverage. The stock, or portions of the stock, has been surveyed annually by the National Marine Fisheries Service (NMFS) EBS continental shelf summer trawl survey since 1975 (Chilton et al. 2011). However, the remoteness and vast geographic distribution of the EBS snow crab stock, coupled with the often severe weather and the broad extent of winter sea ice, pose significant limitations to field research and data collection programs. As a result, through the 1990s, limited research was conducted toward estimating fundamental productivity parameters and understanding population processes of EBS snow crab despite the large economic importance of the commercial fishery. Notable research during the 1980s included a tagging study that provided growth per molt data (McBride 1982) and investigations on life history and population dynamics (Somerton 1981a, 1981b), larval development (Incze et al. 1984), larval distribution relative to oceanography and adult female distribution (Incze et al. 1987), and predation by Pacific cod *Gadus macrocephalus* (Livingston 1989). Research on EBS snow crab during the 1990s included studies of post-terminal molt longevity and age at shell condition (Nevissi et al. 1996); spatial, temporal, and demographic trends of the stock (Otto 1998); and efficiency of the summer trawl survey gear in capturing snow crab (Somerton and Otto 1999). Additionally, in 1991, the Alaska Department of Fish and Game (ADF&G) crab fishery observer program was expanded to include partial coverage of the EBS snow crab fishery, providing detailed information on fishery practices and catch, as well as establishing a platform for collecting biological data during the winter fishery (Boyle and Schwenzfeier 2002).

The overfished declaration for the EBS snow crab stock in 1999 and the resulting reduced harvest levels motivated increased research on the EBS snow crab stock and fishery, which are briefly reviewed here. In 2000, the U.S. Congress appropriated funds to the State of Alaska for Bering Sea Snow Crab Fishery Restoration Research (NOAA Cooperative Agreement NA17FW1274). A stock assessment model for EBS snow crab was developed to evaluate rebuilding plans for the stock (NPFMC 2000), which has since been regularly reviewed and revised and is currently used in the federal stock status determination process (Turnock and Rugolo 2010). Existing data on spatial distribution and recruitment patterns of the stock were analyzed (Zheng et al. 2001). A workshop was held early in 2001 to develop hypotheses on the factors and mechanisms affecting year-class strength in EBS snow crab (Kruse et al. 2007). The federal appropriation funded new field and laboratory research during 2001–2005 on reproductive biology of EBS female snow crab, reproductive potential and life history of EBS snow crab, assessment of terminal molt in male snow crab, and a pilot study on development of age determination methods for snow crab (Pengilly 2005). Additionally, in 2001, ADF&G funded research on the reproductive dynamics of EBS female snow crab (Armstrong et al. 2004) using funds appropriated by Congress to the State of Alaska for Bering Sea Crab Research (NOAA Award NA16FN1275). The research initiated in 2000–2001 resulted in numerous publications and symposium presentations (e.g., Ernst et al. 2005; Orensanz et al. 2005; Tamone et al. 2005; Webb et al. 2006, 2007) that have greatly added to the understanding of factors affecting productivity of the EBS snow crab stock. Since that pulse of research motivated by the 1999 overfished declaration, research on the EBS snow crab stock and fishery has continued. For example, in 2005 ADF&G initiated a program to annually monitor and estimate reproductive potential in the EBS snow crab stock (Gravel and Pengilly 2007; Slater et al. 2010) and conduct research on the selectivity of snow crab by the annual NMFS EBS summer trawl survey, which has been conducted cooperatively by NMFS and the Bering Sea Fisheries Research Foundation (BSFRF; Somerton, D. A., K. Weinberg, and S. Goodman, 2010, unpublished report, Snow crab selectivity by the NMFS trawl survey, NMFS Alaska Fishery Science Center, Seattle, WA; NPFMC 2011). Notably, the North Pacific Research Board has funded projects including studies of female reproductive output of EBS snow crab, reproductive potential of male EBS snow crab, models of transport and survival of EBS snow crab larvae, prediction of the effects of climate warming on the size and growth of snow crab in the northern EBS, development of biological reference points for the EBS snow crab stock, and evaluations of the effects of uncertainty in snow crab recruitment on management strategies (www.NPRB.org). Results of recent research have included the development of conceptual models for spatial dynamics and recruitment pulses in the EBS snow crab stock (Parada et al. 2010) and development of hypotheses on the mechanisms affecting temporal and spatial variation in the size at terminal molt to maturity in female EBS snow crab (Orensanz et al. 2007).

By early 2010, we (the authors of this report) recognized the need for a broad and in-depth review of the research that has been conducted on EBS snow crab in the decade since the 1999 overfished declaration. We concluded that, to better determine the direction of research in the future, it was time to step back and assess the current state of knowledge on the EBS snow crab stock and the current understanding of fishery effects on the stock. Although a multitude of research priorities have been suggested for the EBS snow crab stock since the overfished declaration (e.g., Webb and Woodby 2011; NPFMC 2010; Turnock and Rugolo 2010), we saw the need for a meeting of specialists to reevaluate those research priorities in the context of 1) the results of research on EBS snow crab in the past decade, 2) the results of research on eastern Atlantic stocks of snow crab, 3) the EBS snow crab stock assessment model, 4) the conceptual models that have been developed for EBS snow crab stock dynamics, 5) existing data-collection programs, and 6) the logistical realities of performing research on and collecting data from the EBS snow crab stock. Moreover, given the logistical problems associated with studying the EBS snow crab stock, we felt that such a meeting would only be a success if it resulted in the formulation of realistic and effective approaches for collecting the data needed to address priority research objectives. Discussions and correspondence with colleagues in the EBS snow crab research community during 2010 revealed support for convening a meeting, which led us to organize the workshop on which we report here.

The workshop was held in Seattle, WA, during 22–24 February 2011, and it brought together international and regional experts on the biology, ecology, stock assessment, and fisheries management of snow crab. During the planning of this workshop, a list of invited workshop participants was developed with the intent to provide a balanced representation of research biologists, population process modelers, stock assessment analysts, and supervisors of data-collection programs. Although not all invitees were able to attend the workshop, the final list of attendees, including members of the EBS commercial crab industry, provided the breadth and depth of expertise that was hoped for when the workshop was first envisioned. The three-day workshop was split evenly into two sessions. The first session consisted of a symposium of presentations briefly summarizing the current status of our knowledge of snow crab, methods and issues relevant to stock assessment, fishery management, ongoing data-collection programs in the EBS, and current research on EBS snow crab. The second session was an open discussion focused on the workshop goals:

1. identify key uncertainties, poorly estimated stock productivity parameters, and gaps in the understanding of population processes of snow crab in the EBS, especially relative to the information needed for management of the EBS commercial fishery;

2. establish priority research objectives for addressing the identified uncertainties, poorly estimated parameters, and gaps in understanding; and

3. suggest approaches for achieving those research objectives.

Seven priority objectives for new or continuing EBS snow crab research were identified during the workshop. Workshop participants offered suggestions for possible methods or approaches toward attaining each identified research objective, either through modifications of existing data-collection programs and analyses of existing data, or through new research initiatives.

This report provides a list of the seven priority objectives for EBS snow crab research that were identified during the workshop discussion, a summary of the workshop participants' rationale for identifying those objectives as priorities, and a summary of the workshop participants' suggested methods or approaches for achieving those research objectives. We recognize the inherent difficultly in capturing all the elements of the workshop discussions, but we strived to faithfully represent the findings of the workshop and the consensus of workshop participants in this summary. Additionally, this report contains appendices that provide the agendas for the workshop symposium and discussion and the abstracts submitted by the speakers for each symposium presentation.

It should be noted that the information presented in this report is limited to information that was available at the time of the workshop and the priorities for research presented in this report are those that were identified by workshop participants during the workshop. This report does not present information that has become available since the time of the workshop, does not remark on any advances that have been made since the workshop toward the research priorities that were identified during the workshop, and does not include any new research priorities that have been identified since the workshop. Publications that appeared in the literature or as reports after the workshop are only referenced in this report if drafts of such publications were substantially completed and were submitted for publication by the time of the workshop and information contained in such publications was presented and discussed during the workshop.

## A NOTE ON TERMINOLOGY

*Snow crab ontogenetic stages.* The terminology for ontogenetic stages of snow crab used in this report—although not necessarily in the appendices—follows Sainte-Marie et al. (2008). Use of the term *adult* is reserved for males and females that have completed their terminal molt to maturity. *Adult females* are distinguished externally from preterminal-molt females by a broad abdomen relative to carapace width and the presence of setiferous pleopods. *Adult males* are distinguished externally from preterminal-molt males by large chelae relative to carapace width. A recently molted adult female that has not extruded her first clutch of eggs is referred to as a *nulliparous female*, whether or not she has been mated. A *primiparous female* is an adult female carrying her first clutch of eggs, whereas a *multiparous female* is an adult female carrying her second or subsequent clutch. *Pubescent female* refers to a preterminal-molt female with developed ovaries and mature oocytes during a brief period just before the terminal molt. Prior to the pubescent stage, preterminal-molt females with ovaries that are apparent upon dissection are referred to as *prepubescent females*. Preterminal-molt males with gonads that are apparent upon dissection and vas deferens containing fully formed sperm and spermatophores are referred to as *adolescent males*. *Immature* refers to males or females in postsettlement instars before their gonads or ovaries are apparent upon dissection. Finally, we use the term *juvenile* in this report when referring to males or females in unspecified postsettlement, preterminal-molt stages.

Note, however, that various authors, including contributors to the symposium portion of this workshop, have used alternative terminologies for ontogenetic stages of snow crab (Sainte-Marie et al. 2008). We did not edit the terminology used by symposium contributors for ontogenetic stages in the titles or abstracts that they provided (Appendices A1 and A4) to conform to the terminology we use in the body of this report. Some contributors used the term *mature* when referring to adult males or primiparous and multiparous females, *adult males* when referring collectively to adolescent and adult males, and *immature* when referring to juvenile stages (i.e., unspecified postsettlement, preterminal molt stages).

*Domains of the EBS continental shelf*. We follow Ernst et al. (2005) in this report by using the three recognized depth zones or *domains* of the EBS continental shelf (Schumacher and Stabeno 1998) when discussing the spatial distribution of EBS snow crab: the *Coastal Domain* (shoreward from the 50 m isobaths), the *Middle Domain* (between the 50 m and 100 m isobaths), and the *Outer Domain* (between the 100 m isobath and the continental shelf break).

# PRIORITY EASTERN BERING SEA SNOW CRAB RESEARCH OBJECTIVES

## Characterize the spatial-temporal distribution of males relative to mating and reproductive output

A. Rationale

Pubescent female snow crab in the EBS are estimated to terminally molt to maturity, mate as nulliparous females, and extrude their first clutch of eggs mainly during February–March (Ernst et al. 2005; Rugolo et al. 2005). Primiparous and multiparous females, on the other hand, are estimated to hatch their eggs, mate, and extrude a new clutch mainly during April–May (Somerton 1981a, 1982a; Rugolo et al. 2005). Additionally, the distribution by ontogenetic stage of females captured during the summer (June–July) EBS trawl survey strongly suggests that mating of nulliparous females occurs largely in the Middle Domain, whereas mating of females that previously have carried at least one egg clutch occurs largely in the Outer Domain. Juvenile females are concentrated in the Middle Domain and the adjacent margins of the Coastal Domain, primiparous females occur primarily in the Middle Domain and the shallower fringes of the Outer Domain, and multiparous females occur primarily in the Outer Domain and the deeper fringes of Middle Domain (Ernst et al. 2005). Given that spatial-temporal pattern in the mating of female snow crab by ontogenetic stage, knowledge of the distribution of adolescent and adult males by shell-condition category at the time of mating is key to understanding spatial-temporal patterns in data that are collected on female reproductive potential (clutch fullness, spermathecal load, and egg fertilization rates) and to estimating the effects of fishery removals on the stock's reproductive output. Adolescent males may be able to mate only with soft-shelled nulliparous females, and reproductive potential of adult males increases with time since terminal molt (Sainte-Marie et al. 1997, 2002, 2008). Additionally, sex ratios determine the sperm availability for females (Sainte-Marie et al. 2002) and trigger or modify social-behavioral responses, such as mate guarding by males (Rondeau and Sainte-Marie 2001).

Data on the distribution of males are generally available for only two seasonal windows: during the summer trawl survey and the winter fishery (occurring primarily during January–March, although some fishing can occur into May). There are two weaknesses to the survey data in terms of understanding male distribution relative to mating activity: 1) the June–July survey timing follows the time of mating by 1–6 months, depending on the ontogenetic stage of the females being mated and the survey station location; and 2) the data collected during the summer survey are not sufficient to determine the ontogenetic stage (immature, adolescent, or adult) of all captured males. Data collected during the winter fishery are spatially limited to where the fishery is prosecuted, which is primarily close to the shelf edge, in deeper grounds and further west or southwest in the Outer Domain than where most adult females are believed to be mated. Retained and nonretained catch of males during the winter fishery consists almost exclusively of adult males, regardless of size (NPFMC 2000), although it is unclear whether that is attributable to distributional differences between adolescent and adult males or to selectivity for adult males over adolescent males by the pot fishing gear (Sainte-Marie and Turcotte 2003). Distribution patterns from subsequent years of summer survey data suggest a general south/southwest ontogenetic migration by males from the Middle Domain to the Outer Domain (Otto 1998; Zheng et al. 2001; Orensanz et al. 2004), a pattern that was supported by a tagging study of adult males between summer release and winter recovery (Pengilly 2006). Whether some or all adult males present near the shelf edge during the winter fishery move to shallower waters in the Outer Domain for mating with primiparous and multiparous females or to the Middle Domain for mating with nulliparous females remains unknown.

B. <u>Suggested Methods and Approaches</u>

a. Existing programs and data

i. *Survey data on male maturity* – There is a need to identify the maturity status of males during the NMFS EBS trawl survey through the collection of additional data, including chela height.

- *Determining size at transition from immature to adolescent*: Data from Canadian snow crab stocks suggests that onset of adolescence consistently occurs over a narrow size range (37.5 to 39.2 mm carapace width [CW]) that is close to the minimum size of adult males (~ 40 mm CW; Sainte-Marie et al. 1995). If that were also true for the EBS snow crab stock, adolescent males could be distinguished from immature males with reasonable reliability during the summer trawl survey on the basis of size. However, data sufficient to determine the size of onset of adolescence in EBS snow crab males are not available. A program could be initiated in conjunction with the NMFS EBS trawl survey to sample males throughout their size range and survey distribution to determine the size at which this transition occurs. Sampling should be sufficient to detect spatial-temporal variation. Once this minimum size has been reliably estimated, continued sampling should not be necessary.

- *Distinguishing between adult and adolescent*: Ideally, all sampled males during the survey should be measured for carapace width and chela height to 0.1 mm, the resolution that allows adult males to be consistently distinguished from adolescent males (Rugolo et al. 2005). If this resolution is not feasible due to existing demands for data collection during the multispecies trawl survey, subsampling protocols could be established for chela height measurements that are sufficient to estimate the density and size distribution of adult males at each station where male snow crab are captured during the survey.

ii. *Fishery data on male maturity* – Earlier analyses of chela height and carapace width data collected by ADF&G Shellfish Observer Program have been cited to conclude that retained and discarded males captured during the fishery are adult (NPFMC 2000). Those data, with measurements recorded to the nearest 1 mm, and more recently with measurements to the nearest 0.1 mm, should be reviewed relative to that conclusion and relative to the need for continued data collection.

iii. *Archival tag studies of male movement* – Adult males captured during the commercial fishery were tagged with archival pressure-temperature recorders in a cooperative NMFS-ADF&G-Industry study with the objective of estimating the spring-to-winter movements of males (principal investigators: Dave Somerton and Dan Nichol, Appendix A4 abstract). Depth and temperature data from recovered tags reveal different patterns of movement from individual males. We hope future analysis of tidal signals captured by recovered tags can be resolved to determine males' location over time and provide a better understanding of movement patterns.

b. New initiatives

i. *Development of new approaches to studying movement of males* – To date, studies attempting to estimate movements of male snow crab in the EBS have involved tagging studies that relied on the commercial fishery for the recovery of tagged crab (Pengilly 2006). Such studies can only provide information on those males that are present at the fishing grounds at the time of the fishery. Fishery-independent approaches need to be developed that can provide information on movements of adult males relative to the mating periods. A promising suggestion is the use of sonic tags, an approach that is being developed for multiple crab species and tested on red king crab in nearshore Kodiak waters (principal investigators: Christian de Moustier and Bob Foy). Application of that approach to the study of male snow crab in the EBS would require the use of tags and tag receiver technology capable of studying movements.

ii. *Field studies to determine timing of mating* – Field studies are needed to better understand the mating periods in the EBS, including spatial, temporal, and environmental factors relative to female ontogeny and larval release.

iii. *Direct observations of mating and sex ratios during mating* – Direct observations are needed to document sex ratios during the mating season, with the ability to estimate the size, shell condition, and ontogenetic stage of males mating with females, both in the Middle Domain (nulliparous females) and the Outer Domain (primiparous and multiparous females). Ideally, observations should span the period of mating within an area. A cross-shelf (NE-to-SW) transect sampling approach may be a useful design. Given the seasonal presence of ice, an approach to consider in this regard would be the use of autonomous underwater vehicles. A location where postmating aggregations of multiparous females are known to occur (e.g., NMFS EBS trawl survey station K24; see below) would make an interesting focal point for initiating direct observations of mating and sex ratios.

iv. *Field studies to determine fine scale spatial distribution of mating* – Direct observations using a towed benthic imaging system at the NMFS EBS trawl survey station K24 during July 2008 showed that multiparous females can be aggregated within a relatively small area shortly after the mating period (G.E. Rosenkranz, Biometrician, ADF&G, Kodiak, personal communication). EBS trawl survey data from station K24 during the summer shows that such areas of aggregation are consistently sampled over periods of at least a decade (D.A. Somerton, NMFS-AFSC, Seattle, personal communication). Field studies to monitor the spatial-temporal change in male and female density by size, shell condition, and reproductive status at such sites from the time of larval release through mating could provide valuable insights into the reproductive dynamics of multiparous females.

## Estimate variability in female reproductive potential

A. Rationale

The federal process for EBS snow crab stock status evaluation and overfishing determinations currently uses adult male biomass as the index of stock reproductive potential (Turnock and Rugolo 2010). However, trends in adult male biomass may not correspond with trends in female reproductive potential, and development of an index that incorporates female reproductive potential is a priority. Indices based on monitoring egg clutch fullness during stock assessment surveys were evaluated (Orensanz et al. 2005), but concerns were raised that this method may not detect females carrying unfertilized embryos (Turnock and Rugolo 2010). Female reproductive potential may also fluctuate with variable stock demography (Orensanz et al. 2005), sex-ratio (Sainte-Marie et al. 2002, Sainte-Marie et al. 2008), and environmental factors, including induction of a biennial reproductive cycle below a threshold temperature (Sainte-Marie et al. 2008). The proportion of adult females on a biennial reproductive cycle modifies the effective sex ratio and may markedly decrease the reproductive contribution of a cohort due to less frequent spawning and natural mortality acting over a longer duration of embryo incubation.

Priorities for research on reproductive potential of EBS snow crab include obtaining data on sperm reserves and egg fertilization rates of adult females and studies investigating the effects of sex ratios and the male-only fishery on male and female reproductive potential (Sainte-Marie et al. 2008, Webb and Bednarski 2010). Data on female sperm reserves and egg fertilization rates can provide insight into frequency of mating and whether sperm reserves provide a buffer against future sperm limitation, but such data must be sufficient to characterize spatial-temporal trends and the effects due to the size and post-terminal molt age of adult females. Recent studies observed low sperm reserves for primiparous females in the EBS relative to Atlantic Canada (Slater et al. 2010), but the factors associated with that pattern, including effective sex ratio and the maturity status of males participating in primiparous mating, are poorly characterized.

B. Suggested Methods and Approaches

a. Existing programs and data

i. *Incorporate female reproductive potential data into management* – There is a need to evaluate how to best integrate data on female reproductive potential into EBS snow crab stock assessment and reference point estimation and whether current efforts by ADF&G (principal investigators: Laura Stichert [Slater], Joel Webb, and Doug Pengilly; Appendix A4) provide the data needed for such integration.

ii. *Assess patterns of sperm reserves with ontogeny* – A long-term study of sperm reserves in primiparous and early multiparous female snow crab in the EBS is ongoing (principal investigators – Laura Stichert [Slater], Joel Webb, and Doug Pengilly; Appendix A4). Analyses to date have focused on data from primiparous females (Slater et al. 2010). There is also a need to analyze data from multiparous females. Comparisons between sperm reserves of primiparous and early multiparous females may provide insight into repeated mating with ontogeny and possible effects of the size and shell condition of available males in each group's geographic distribution.

iii. *Improve estimation of abundance and distribution of females reproducing biennially* – Development of better indicators for estimating the proportion of females on a biennial cycle in a given year, such as ovarian maturation state, embryo development stage, and clutch color, would be useful to improve estimation of this key reproductive parameter in relation to bottom temperature. Although egg color has proven a useful indicator for other snow crab stocks (Kuhn and Choi 2011), this approach has not been successful in the EBS, possibly due to survey timing relative to embryonic development.

iv. *Compare recent data with previous studies* – Comparison of fecundity, sperm reserves, and ovary development data from the current long-term study in the EBS (principal investigators: Laura Stichert [Slater], Joel Webb, and Doug Pengilly; Appendix A4) with data collected in 1992 and 1993 (principal investigators: J.M. [Lobo] Orensanz and David Armstrong) and during a seasonal study conducted in 2002 and 2003 (Rugolo et al. 2005) could provide important insights into temporal variability under contrasting stock-abundance levels and environmental conditions.

v. *Seasonal data on reproduction and molting* – Data collected seasonally from EBS snow crab during 2002–2003 contain valuable information on molt timing, female reproductive condition, and the female reproductive cycle (Rugolo et al. 2005). Further analysis of these data and dissemination of the results and findings through publication in the peer-reviewed literature is strongly encouraged.

b. New initiatives

i. *Improve sperm cell count methods* – Development of methods to count snow crab sperm cells by flow cytometry or staining could decrease processing time and assist in identifying viable sperm cells.

ii. *Improve understanding of variability in clutch fullness* –Turnock and Rugolo (2010) observed reduced clutch fullness in a portion of the adult female stock. A reduction in clutch fullness may result from a variety of factors, including (1) retention of oocytes in the ovaries, which may be due to sperm limitation; (2) loss of unfertilized or otherwise unviable eggs; (3) consumption or damage caused by brood parasites; (4) mating soon after egg extrusion, which occurs most commonly in first-time breeding females and may result in loss of weakly attached eggs; and (5) senescence for some of the multiparous component of the female population. Mating experiments and direct observations in a laboratory setting, in conjunction with an evaluation of the spatial-temporal occurrence of varying clutch fullness and related environmental variability and stock characteristics, may improve understanding of the mechanisms responsible for the observed spatial and temporal patterns in reduced clutch fullness.

## Improve understanding of larval life history and behavior

A. <u>Rationale</u>

Results of stimulations of larval transport using the Regional Ocean Model System oceanographic model for the EBS, coupled with the ontogenetic migration and spatial distribution of postsettlement ontogenetic stages of snow crab in the EBS, support the *environmental ratchet hypothesis* (Orensanz et al. 2004) for the spatial and stock-rebuilding dynamics of EBS snow crab and have important implications for understanding the importance of fishery effects relative to environmental effects on those dynamics (Parada et al. 2010). However, aspects of the life history and behavior of snow crab larvae in the EBS that could affect their transport are poorly understood, and the results of those simulations may be sensitive to some tentative assumptions that were necessarily made for the simulations. Research that provides information on the timing and duration of zoeal stages and the megalopa stage in a variable environment, the ability of larvae to modify their position in the water column, the ability of megalopae to respond to physical cues during settlement, and features of larval ecology that could influence transport is needed to refine the conceptual model of larval snow crab transport. Additionally, more recently developed models that resolve some oceanographic features that probably influence larval advection (e.g., eddies and fronts) should be used to simulate larval transport.

B. <u>Suggested Methods and Approaches</u>

a. Existing programs and data

i. *Assess existing plankton samples* – Explore status and relevance of plankton samples recently collected in the EBS (i.e., BEST-BSIERP Project, NMFS EBS shelf survey) for validation of predicted larval distributions in space and time.

ii. *Empirical validation of model predictions* – Data from drifters deployed on the EBS shelf (e.g., Danielson et al. 2011) may be valuable for comparison with advection model results.

b. New Initiatives

i. *Improved oceanographic modeling* – A study of advection of larval Tanner crab using higher resolution ocean models is currently underway (principal investigators: Jonathan Richar and Gordon Kruse), which may provide insight into patterns of advection that are also important for EBS snow crab. If results indicate differing patterns of advection based on model resolution, then use of higher-resolution models would be recommended for snow crab.

ii. *Location, timing, and initiation cues of larval release* – Fieldwork to determine the distribution of adult females by ontogenetic stage during the timeframe of larval release (mainly, April–May) on the EBS shelf would better inform model-based predictions of larval advection. Such work could additionally be useful to resolve relationships between timing and location of larval release, ice edge, and primary production. Understanding patterns of larval release in response to endogenous or exogenous cues including tides or primary production (e.g., Kuhn et al. 2011) could also be important for refining estimates of larval release location and timing in larval advection modeling.

*iii. Larval behavior and modeling* – Laboratory studies of larval ecology including rheotaxis, phototaxis, thermal preferences, duration of stages at varying temperatures, settlement cues, and substrate preference of megalopae are needed to improve and/or validate model assumptions and predictions. Results of laboratory studies, megalopae collection techniques (Kon et al. 2003), and continued monitoring of groundfish stomachs for the distribution and relative abundance of early benthic stages could be useful for informing spatial patterns of settlement.

## Estimate growth throughout ontogeny

A. <u>Rationale</u>

Population modeling of EBS snow crab is based on a stock assessment model that requires accurate estimates of growth, and there is a need for improved information on snow crab growth throughout its life history. Immature crab undergo multiple molts over the first two years of benthic life and then enter into more regular annual molt cycles until their terminal molt. Improved estimation of snow crab growth, particularly growth per molt (molt increment) and size at which male crab enter adolescence, is needed to better characterize snow crab life history. The size range at which reproductive function is attained may allow a better understanding of factors that constrain the size at which crab enter their terminal molt.

An improved understanding of growth under different temperature regimes and geographic locations is important relative to predicted warming trends in the eastern Bering Sea. It was suggested from studies on Atlantic snow crab populations that, for immature instars, the molt increment is less sensitive to temperature than is the molt interval and, therefore, instar size structure may be conserved between populations of snow crab (Burmeister and Sainte-Marie 2010). It would be useful to test the hypothesis that variability in temperature, as well as other factors such as fishing pressure and prey availability, does not contribute to changes in molt increment exhibited by snow crab over a broad range of sizes.

B. Suggested Methods and Approaches

a. Existing programs and data

i. *Analysis of size-frequency data for growth* – Snow crab obtained from cod stomach contents (Chabot et al. 2008) and the NMFS EBS trawl survey provide modal information on the size of juvenile and immature snow crab. Additionally, size-frequency data for juvenile snow crab from the NMFS-BSFRF selectivity study (Somerton, D. A., K. Weinberg, and S. Goodman, 2010, unpublished report on snow crab selectivity by the NMFS trawl survey, NMFS Alaska Fishery Science Center, Seattle, WA) could be used to validate growth increment estimates. Although extrapolations may be made over a broader size range than data are available for, molt increments of adolescent males and prepubescent and pubescent females differ from those of immature crab (Sainte-Marie et al. 1995; Alunno-Bruscia and Sainte-Marie 1998), and extrapolation of growth data obtained from immature crab of unknown gender to infer growth of later, pre-adult stages could be problematic.

*ii. Comparison of data from different sources* – Molt increments inferred from modal analysis of size-frequency data from cod stomachs and surveys should be compared to the ongoing laboratory-based study of snow crab growth in which molt increment data is obtained from snow crab held in the laboratory until molting (principal investigators: Laura Stichert [Slater] and Doug Pengilly, Appendix A4 abstract).

iii. *Conservation of growth increments* – The hypothesis that molt increments of immature crab are conserved between populations of snow crab in the EBS and the Gulf of Saint Lawrence should be tested. If molt increments are found to be conservative, evaluation of the incorporation of growth data from other populations of snow crab (e.g., Sainte-Marie et al. 1995) to the EBS stock management process is recommended.

b. New initiatives

i. *Evaluation of laboratory holding effects* – Because the duration of holding in a laboratory prior to molting reduced the molt increments for Tanner crab (Stone et al. 2003), evaluation of potential holding effects for snow crab is recommended. A study in which crab are held in the natural environment or are held in a laboratory for a shorter duration prior to molting is recommended to validate the applicability of laboratory-based growth estimates to populations in nature.

ii. *Identification of ontogenetic factors affecting growth* – Because snow crab partition energy between growth and reproduction, it is important to identify the points during life history at which relative growth varies, such as at the terminal molt for females. While the terminal molt in males appears to have little or no effect on relative growth, it has been suggested that the molt from immaturity to adolescence is important. There are allometric changes relative to body size for both chela height (Sainte-Marie et al. 1995) and periopod length (Chabot et al. 2008) at the molt to adolescence in male crab, so evaluation of detailed data collected during the EBS survey, possibly augmented with additional data-collection procedures, could provide the size range at which this molt occurs in EBS (as summarized previously under objective I). Subsequent growth studies focused on this size range of male snow crab would then be recommended to better understand how growth may be affected at this molt.

iii. *Laboratory analysis of factors affecting growth* – Laboratory studies may provide useful information on biotic factors, including density (Sainte-Marie and Lafrance 2002), and abiotic factors affecting molt interval and molt increment. Because there is a shorter intermolt period for immature crab undergoing multiple molts per year (Sainte-Marie et al. 1995), early instars (I–V) may be best suited for such studies.

## Estimate natural mortality

A. Rationale

Improved estimation of natural mortality is critical for incorporation in stock assessment models and a better understanding of life history, particularly reproductive lifespan. Estimation of this parameter has been hampered by the difficulty in assessing age and longevity of snow crab. The utility of the lipofuscin-content technique for aging EBS snow crab was investigated, but age estimates using that technique have not been validated (Shirley and Bluhm 2005). Snow crab longevity after benthic settlement in the EBS was inferred from estimates of age at the terminal molt and estimates of longevity post-terminal molt (Turnock and Rugolo 2010). Snow crab experience their terminal molt over a range of ages; females are estimated to terminally molt at ages ranging from 4.5 to 7.5 years, most often at 5.5 or 6.5 years (Alunno-Bruscia and Sainte-Marie 1998; Ernst et al. 2012), whereas males may terminally molt at ages ranging from 4.5 to 11.5 years (Alunno-Bruscia and Sainte-Marie 1998; Orensanz et al. 2008). Maximum age post-terminal molt was estimated at 6–7 years from a small sample of EBS male snow crab using radiometric techniques (Nevissi et al. 1995; Ernst et al. 2005). Post-terminal molt longevity of male snow crab in an unfished eastern Canada population was estimated conservatively at 7.7 years (Fonseca and Sainte-Marie 2008). While dactyl wear was shown to be useful for estimating the post-terminal molt age of male snow crab in an eastern Canada population (Fonseca and Sainte-Marie 2008), application of that method to snow crab in the EBS was ineffective, likely due to the prevalence of a soft bottom seafloor (L. M. Stichert, Fishery Biologist, ADF&G, Kodiak, personal communication).

Factors that affect natural mortality include predation, cannibalism, competition, habitat availability, disease, climate variability, and interactions among these factors. A comparative study across Atlantic and Pacific snow crab populations suggest that above-average temperatures during the larval phase are associated with poor recruitment, while increased biomass of cod (predators) does not have a consistent effect on snow crab recruitment (Marcello et al. 2010). Variability in snow crab recruitment over time is pronounced, with oscillating periods of strong versus weak cohort abundance referred to as recruitment waves. Snow crab in the EBS are characterized by recruitment waves with a mean period of 7 years for adult females (Ernst et al. 2012). Because males undergo the terminal molt over a broader range of instars and this molt often lags behind that of females, recruitment of a strong cohort to maturity occurs over multiple years and may result in an oscillating adult sex ratio (Sainte-Marie et al. 2008). Although predation and disease (i.e., bitter crab syndrome) may dampen recruitment waves, it is unlikely they are a driving force behind the patterns observed (B. Sainte-Marie, Department of Fisheries and Oceans, Mont Joli [Québec], Canada, personal communication).

Natural mortality rates probably vary with size and age, with higher rates expected for juvenile and immature stages and a leveling off to a lower mortality rate with increased age and size, followed by increased mortality with age due to the effects of senescence (Vetter 1988). Also, due to mating costs, post-terminal molt mortality is presumed higher on females than on large adult males (B. Sainte-Marie, DFO, Mont Joli [Québec], Canada, personal communication). Size- and age-structured mortality curves may be appropriate, using size up to the terminal molt and shell condition or another proxy for age after the terminal molt.

B. <u>Suggested Methods and Approaches</u>

a. Existing programs and data

i. *Management Strategy Evaluation (MSE)* – A study to assess the robustness of the stock assessment method to variability in estimated parameters is currently underway (principal investigators: Cody Szuwalski and Andre Punt, Appendix A4 abstract). It would be useful to evaluate a wide range of values for natural mortality (*M*) and consider varying *M* with size and with age relative to terminal molt.

ii. *Mark–recapture studies* – Analysis of data from a study of tagged crab releases and fishery recoveries over multiple successive years in the Gulf of St. Lawrence (Fonseca et al. 2008) may provide estimates of natural mortality through comparison of the recovery rate (in a single year) of one year's tags (relative effort) versus the previous years' tags. However, the influence of violations of the assumptions implicit in this approach, particularly the inconsistency between release and fished locations between years and the assumed movement of crab between successive years, may be large.

iii. *Cannibalism studies* – A model-based study is in progress to improve understanding of possible cascade effects of cannibalism moderated by effective prey size (large-sized crab prey on intermediate-sized crab, intermediate-sized crab prey on new settlers) (principal investigators: Bernard Sainte-Marie and Kim Émond). An objective of this study is to understand how fishery-induced reductions in density of large males may affect cannibalism rates, prey switching behavior, and other factors that may control year class strength of 3 mm (settlers) to 10 mm CW early benthic stages.

*iv. Diet analysis and cannibalism* – Evaluation of snow crab diet was conducted as part of a study in the northern Bering Sea (principal investigators: Jason Kolts and James Lovvorn, Appendix A4 abstract). Additionally, monitoring of snow crab diet during the NMFS EBS trawl survey was initiated (principal investigators: Bob Foy, Kerim Aydin, and Frank Morado). Those studies could allow analysis of cannibalism rates throughout snow crab distribution and provide estimates of effective prey size. It would be useful to compare cannibalism rates among regions of varying crab density and over multiple years to infer whether cannibalism is a driving factor of recruitment waves.

v. *Demographic approaches to the estimation of natural mortality* – Retrospective analysis of differences in the density and abundance of new-shell condition snow crab in one year and old-shell condition crab in the next year could provide estimates of natural mortality. Because new-shell females may immigrate to the survey area from the north, analysis could be focused on smaller geographic scales and/or periods when female immigration is not indicated.

b. New initiatives

i. *Age estimation* – Evaluate effectiveness of new techniques in extractable lipofuscin (Ju et al. 1999; Puckett et al. 2008) for snow crab and determine whether this approach can provide a *rapid assessment* to estimate age and/or validate other age proxies. Variability in the thermal history of snow crab over their life history may be a confounding factor.

ii. *Average lifespan* – Approaches that would estimate the average lifespan of snow crab are encouraged, because these estimates would be more useful to the stock assessment process than existing estimates of maximum longevity.

iii. *Effective tagging techniques* – Development of tags that are retained through molting and/or archival tags (e.g., those that release after death) are encouraged for studies of movement and survival of snow crab of various sizes and maturity statuses.

C. Other Considerations

i. *Climate effects on natural mortality* – Predicted climate variability may influence duration of instars, which decrease with temperature. This can impact age-at-size estimates and duration at vulnerable sizes (for cannibalism and/or predation).

## Estimate total fishing-induced mortality

A. Rationale

Commercial harvest is just one component of fishing mortality. Sound fishery-management strategies must fully account for all forms of fishing mortality, as required by the Magnuson Stevens Fishery Conservation and Management Act. Three forms of fishing-induced mortality besides landings include the following:

- Handling mortality of discarded females and sublegal males caught in the directed fishery.
- Bycatch mortality of snow crab caught and discarded in other crab fisheries and by fisheries for groundfish and scallops.

- Mortality experienced by crab that are affected but not caught by fishing gear on the seafloor. Examples include crab that pass under a scallop dredge or trawl footrope, those struck by other components (e.g., warps, doors) of mobile bottom-contact fishing gear, and those crushed by pots.

The majority of incidentally caught and discarded snow crab are taken during crab fisheries, mostly in the directed snow crab fishery (Turnock and Rugolo 2010). Among the groundfish fisheries, most snow crab bycatch is taken in trawl fisheries for yellowfin sole, flathead sole, and Pacific cod (Turnock and Rugolo 2010). To account for the impacts of this bycatch on the snow crab stock, it is necessary to have accurate estimates of mortality rates experienced by crab associated with the capture, handling, and discarding processes in these fisheries. Currently, management assumes bycatch handling mortality rates of 50% for crab pot fisheries and 80% for trawl fisheries (Turnock and Rugolo 2010).

Mortality experienced by crab that come in contact with fishing gear but are not caught by the gear is currently not considered in the estimation of fishing mortality. Traditional flatfish trawl sweeps cause an estimated 6% mortality rate for snow crab in the path of the trawl (Rose et al. 2010). Although this rate is modest, when expanded by the total areas swept by trawls and the density of snow crab throughout the fishing area, the population-level effects may be significant.

Errors in estimates of fishing-induced mortality have management consequences. For instance, overestimation of handling and bycatch mortality rates would result in loss of harvest opportunity and possibly premature closures of other fisheries with crab bycatch. Conversely, underestimation of these sources of mortality could result in chronic overfishing.

B. Suggested Methods and Approaches

a. Existing programs and data

   i. *RAMP assessment of mortality during the directed fishery* – A handling mortality study applying the Reflex Action Mortality Predictor (RAMP) relationship developed for snow crab (Stoner et al. 2008) is currently underway (principal investigators: Dan Urban and Liz Chilton, Appendix A4 abstract). Snow crab caught during the directed fishery are tested for reflex responses, which can be related to established mortality probabilities, and mortality rates among treatment groups (i.e., on-deck air temperature, wind speed, and handling practices) will be estimated. Prior to revising bycatch mortality estimates used during management, it would be useful to consider delayed mortality rates in snow crab, given variable mortality responses to cold air exposure for Tanner crab (half of mortalities within 24 hours and most of the rest within 8 days) and red king crab (many mortalities during the molting process 47–120 days after exposure; Carls and O'Clair 1990).

   ii. *Mortality from contact with trawl gear* – Results of Rose et al.'s (2010) study of crab mortality from contact with trawl sweeps could be used to model population-level impacts from this form of mortality. A spatial model could consider data on trawl dimensions, tow duration, and number of tows, as well as crab density, by area and bottom type. Insights into the effects of this form of mortality, both historically and currently, would be useful.

iii. *Aerial exposure and injury assessment* – The ADF&G Shellfish Observer Program collected data on aerial exposure and injury rates of snow crab during fishing seasons 1997/1998 to 2000/2001. Data from the 1997/98 and 1998/99 fishing seasons were summarized and reported on (Tracy and Byersdorfer 2000; Byersdorfer and Barnard 2002). Data from the remaining seasons could be reviewed to better assess handling mortality.

b. New initiatives

i. *RAMP assessment of mortality in nondirected fisheries* – Application of the RAMP method to estimate bycatch mortality of snow crab during flatfish and cod trawl fisheries would be useful.

ii. *Additional sources of mortality* – Uhlmann et al. (2009) showed that blue swimmer crab *Portunas pelagicus* with unsealed wounds (and resulting blood loss) experienced significantly higher mortality rates than crab with sealed or no wounds. Additionally, if injured or bleeding crab are more susceptible to parasites (e.g., amphipods) or disease, then mortality rates observed during controlled experiments may not be comprehensive. The means by which a crab is returned to the sea (e.g., sliding down a ramp or tossed over) may affect its condition and survivability. It would be useful to study the effects of crab release methods using tag recovery rates to estimate mortality of crab after they have been released from a vessel. Development of new sonic tags that can be detected by an autonomous underwater vehicle or multibeam sonar may lead to novel approaches to assist such studies.

C. Other Considerations

i. *Ghost fishing by lost pots* – Crab and groundfish pots in state and federal fisheries are required to have biodegradable twine (or galvanic timed release) that creates an opening in the side wall of the pot over time. Lost pots during crab fisheries are reported to ADF&G, and the rates of pot loss have been generally very low since crab rationalization began, with the exception of instances when sea ice coverage progresses quickly over the fishing grounds (H. Fitch, Fishery Biologist, ADF&G, Dutch Harbor, personal communication).

## Improve accuracy and precision of survey-based stock abundance estimates

A. Rationale

The NMFS EBS summer trawl survey is designed to sample both groundfish and crab species to meet stock assessment needs for fishery management plans of multiple stocks. The survey has provided a long time series of abundance and distribution that is the basis for snow crab stock assessment. However, there are recognized shortfalls, particularly with trawl selectivity, spatial coverage, and density estimations of spatially aggregated crab populations.

Research efforts have demonstrated that the NMFS trawl survey underestimates the densities of snow crab in the trawl path. A study conducted in 1997 used an underbag to capture crab that were not captured by the primary net and demonstrated that trawl net effectiveness increased with crab size (Somerton and Otto 1999). More recent work in 2009 and 2010 (Somerton, D. A., K. Weinberg, and S. Goodman, 2010, unpublished report on snow crab selectivity by the NMFS trawl survey, NMFS Alaska Fishery Science Center, Seattle, WA; S. Hughes and D. Somerton, Appendix A4 abstract) compared catches from side-by-side trawling using the NMFS survey net and a Nephrops net, which is considered highly effective at catching small crab. This study was designed to cover the surveyed distribution of snow crab in the EBS and include a range of temperatures, crab densities, substrate types, and depths, which are the primary cofactors thought to affect selectivity of the standard survey trawl. Results are being analyzed to estimate a selectivity curve that can be used to scale up NMFS survey results to provide estimates of male and female snow crab abundance by size class.

The NMFS trawl survey has periodically surveyed additional areas outside the standard survey area, including the northern Bering Sea, where large numbers of small snow crab have been captured. Information on snow crab from areas north of the standard survey area is important for understanding stock abundance, especially given the premise of ontogenetic migration of at least some of these crab into the standard survey area from the north.

B. <u>Suggested Methods and Approaches</u>

a. Existing programs and data

i. *Survey selectivity* – A collaborative NMFS-BSFRF study was conducted in 2009 and 2010 to improve the estimation of survey selectivity in the stock assessment model (principal investigators: Dave Somerton and Steve Hughes, Appendix A4 abstract). It would be useful to consider the assumption that the Nephrops trawl net is 100% efficient as well as the influence of density on selectivity, which may be a factor explaining the pronounced hump in catchability of small males (i.e., 40–50 mm CW).

b. New initiatives

i. *Camera validation of survey selectivity* – Use of underwater cameras might help validate and/or improve trawl selectivity estimates, particularly in relation to areas of high crab density.

ii. *Unsurveyed distribution* – There may be areas outside the standard survey stations that harbor high densities of small snow crab (e.g., shallow, nearshore areas around islands and along the coastal domain), which may be useful for tracking annual recruitment and overall abundance.

iii. *Improved survey precision* – A variety of techniques could be employed to improve the statistical precision of density estimates, including geostatistical methods. To improve precision in areas of high density, additional sampling could include randomly placed secondary samples or finer-scale sampling, perhaps with camera-based methods to detect the spatial extent of aggregations. Field studies could also examine association of aggregations with benthic habitats by crab life stage and determine whether habitat-based modifications to survey density and abundance estimations may be warranted.

C. Other Considerations

i. *Northern Bering Sea Research Area* – As an important element of the benthic fauna in the Northern Bering Sea Research Area, we recommend that snow crab be carefully considered during any planned trawl research in this area. We also recommend communication with communities and governmental bodies in the vicinity of the northern Bering Sea given the heightened concerns with trawl activities in that area.

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# FIGURES

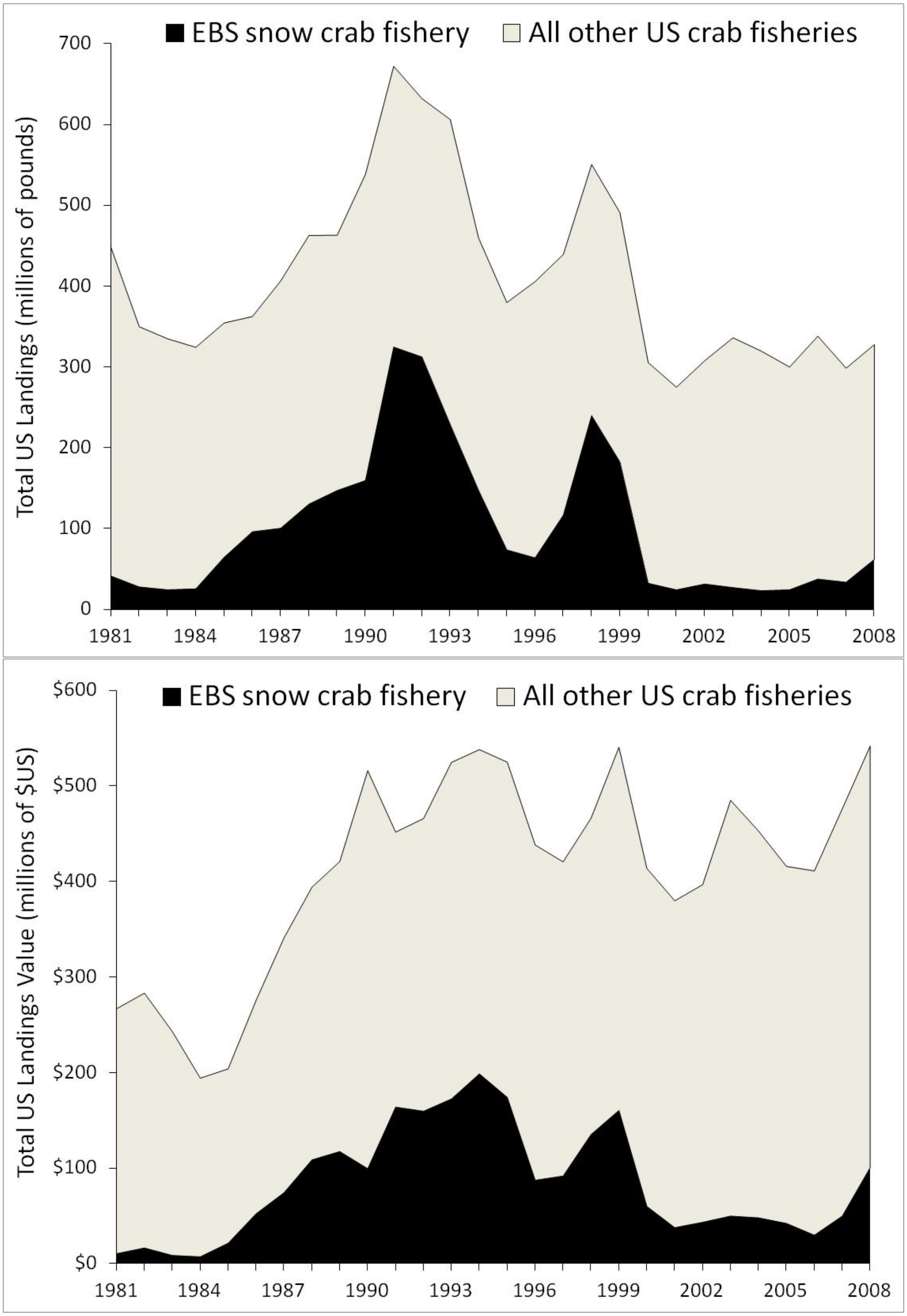


Figure 1.–The total United States commercial crab fishery landings (top panel) and value of landings (bottom panel), 1981–2008, showing the contribution of the eastern Bering Sea snow crab fishery.

*Source*: Data from NMFS, Fisheries Statistics Division, Silver Springs, MD; (http://www.st.nmfs.noaa.gov/st1/commercial/landings/gc_runc.html).

# APPENDIX A

Appendix A1.–Symposium agenda.

# EBS Snow Crab Workshop

**Identifying best approaches for advancing understanding of EBS snow crab biology and incorporating research into fisheries management**

22–23 February 2011

Cirrus Room, Sheraton Seattle Hotel, 1400 Sixth Avenue, Seattle, WA

*Symposium Agenda*

**Tuesday, 22 February 2011**

8:30 a.m. Coffee

9:00 a.m. Welcome, Introductions, and Overview — Douglas Pengilly, Doug Woodby, ADF&G

## BACKGROUND

9:15 a.m. Eastern Bering Sea Snow Crab Stock — Douglas Pengilly, ADF&G, Kodiak
- History of stock
- Overview of cooperative management
- Overview of past research efforts

9:45 a.m. Insights from Snow Crab Research and Management in the Northwest Atlantic — Bernard Sainte-Marie, DFO, Mont-Joli, Canada
- Advancements in understanding snow crab stock dynamics
- Data collection programs that have proven key to successful stock management
- Identified gaps that are key to further understanding snow crab biology, stock dynamics, and fisheries management
- What is next on the horizon
- Q & A (10 min)

10:55 a.m. BREAK

## DATA COLLECTION PROGRAMS FOR EBS SNOW CRAB

11:15 a.m. Stock Assessment Survey — Bob Foy, NMFS AFSC, Kodiak
- Overview of data collection program
- Limitations and sources of uncertainty
- Platform for special projects
- Q & A (5 min)

11:45 a.m.
- Selectivity in the stock assessment survey — Dave Somerton, NMFS AFSC, Seattle; Steve Hughes, BSFRF, Bothell

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|---|---|---|
| 12:15 p.m. | LUNCH | |
| 1:30 p.m. | Fishery Data: Fishery Management Staff<br>• Overview of data collection from the Dockside Sampling Program and fish tickets<br>• Limitations and sources of uncertainty<br>• Platform for special projects<br>• Q & A (5 min) | Heather Fitch<br>ADF&G, Dutch Harbor |
| 1:50 p.m. | Fishery Data: Crab Observer Program<br>• Overview of data collection from the Crab<br>• Observer Program<br>• Limitations and sources of uncertainty<br>• Platform for special projects<br>• Q & A (5 min) | Mary Schwenzfeier<br>ADF&G, Dutch Harbor<br>William Gaeuman<br>ADF&G, Kodiak |
| 2:10 p.m. | Groundfish Diet Data<br>• Overview of data collection program<br>• Limitations and sources of uncertainty<br>• Spatial and temporal trends of snow crab as prey | Kerim Aydin<br>NMFS AFSC, Seattle |

**DATA UTILIZATION & NEEDS**

| | | |
|---|---|---|
| 2:30 p.m. | Fishery Management<br>• Overview & management goals<br>• Key sources of uncertainty<br>• Key unknown or poorly estimated parameters as related to management<br>• Q & A (5 min) | Douglas Pengilly<br>ADF&G, Kodiak |
| 2:50 p.m. | BREAK | |
| 3:10 p.m. | Population Dynamics<br>• Advancements in understanding life history and spatial processes<br>• Key sources of uncertainty<br>• Key unknown or poorly estimated parameters<br>• Q & A (10 min) | Lobo Orensanz<br>CENPAT, Puerto Madryn, Argentina<br>David Armstrong<br>UW, Seattle<br>Billy Ernst<br>UDEC, Concepción, Chile |
| 4:20 p.m. | Stock Assessment and Management Evaluation<br>• Brief overview of snow crab stock assessment model<br>• Key sources of model uncertainty<br>• Key unknown or poorly estimated parameters in S-A model<br>• Overview of management strategy evaluation research<br>• Q & A (10 min) | Andre Punt<br>UW, Seattle |

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| 5:20 p.m. | Summary | Doug Woodby<br>ADF&G, Juneau |
| 5:30 p.m. | Adjourn for the Day | |

**Wednesday, 23 February 2011**

| | | |
|---|---|---|
| 8:00 a.m. | Coffee | |

**OVERVIEW OF CURRENT STUDIES**

| | | |
|---|---|---|
| 8:30 a.m. | • Bycatch mortality in the crab pot fishery | Bob Foy<br>NMFS AFSC, Kodiak |
| 9:10 a.m. | • Movement of mature males | Dave Somerton<br>NMFS AFSC, Seattle |
| 9:30 a.m. | • Reproductive biology | Sherry Tamone<br>UAS, Juneau |
| 9:50 a.m. | • Fecundity | Joel Webb<br>ADF&G and UAF, Juneau |
| 10:10 a.m. | • Female sperm reserves<br>• Growth A | Laura Slater<br>DF&G, Kodiak |
| 10:30 a.m. | • Demography, diet, & reproductive status of snow crab in the northern Bering Sea | Jason Kolts<br>UW, Laramie |
| 10:50 a.m. | Summary | Doug Woodby<br>ADF&G, Juneau |
| 11:00 a.m. | Adjourn for the Day | |

Appendix A2.–Workshop agenda.

# EBS Snow Crab Workshop

**Identifying best approaches for advancing understanding of EBS snow crab biology and incorporating research into fisheries management**

23–24 February 2011

Cirrus Room, Sheraton Seattle Hotel, 1400 Sixth Avenue, Seattle, WA

*Workshop Agenda*

Breaks taken as needed

**Wednesday, 23 February 2011**

1:00 p.m. Workshop Convenes

- Discuss identified research gaps and sources of uncertainty
- Discuss whether existing data can be better incorporated by management

5:00 p.m. Adjourn for the Day

**Thursday, 24 February 2011**

8:00 a.m. Workshop Convenes

- Prioritize research gaps and discuss approaches for addressing them
- Identify research priorities that may be undertaken by existing data collection programs

5:00 p.m. Workshop Concludes

Appendix A3.–Workshop organizers and participants.

| | |
|---|---|
| Organizing Committee | |
| Douglas Pengilly | ADF&G, Kodiak |
| Laura Slater | ADF&G, Kodiak |
| Sherry Tamone | UAS, Juneau |
| Joel Webb | ADF&G, Juneau |
| Doug Woodby | ADF&G, Juneau |
| | |
| Workshop Moderator | |
| Gordon Kruse | UAF, Juneau |
| | |
| Participants | |
| David Armstrong | UW, Seattle |
| Kerim Aydin | NMFS AFSC, Seattle |
| Billy Ernst | UDEC, Concepción, Chile |
| Heather Fitch | ADF&G, Dutch Harbor |
| Bob Foy | NMFS AFSC, Kodiak |
| Bill Gaeuman | ADF&G, Kodiak |
| Scott Goodman | BSFRF, Bothell |
| Anne Hollowed | NMFS AFSC, Seattle |
| Steve Hughes | BSFRF, Bothell |
| Jason Kolts | UW, Laramie |
| James Lovvorn | SIU, Carbondale |
| Franz Mueter | UAF, Juneau |
| Dan Nichol | NMFS AFSC, Seattle |
| Lobo Orensanz | CENPAT, Puerto Madryn, Argentina |
| Edward Poulsen | ABSC, Seattle |
| Andre Punt | UW, Seattle |
| Bernard Sainte-Marie | DFO, Mont-Joli (Québec), Canada |
| Mary Schwenzfeier | ADF&G, Dutch Harbor |
| Dave Somerton | NMFS AFSC, Seattle |
| Cody Szuwalski | UW, Seattle |

*Note:* ABSC – Alaska Bering Sea Crabbers; ADF&G – Alaska Department of Fish and Game; BSFRF – Bering Sea Fisheries Research Foundation; CENPAT – Centro Nacional Patagónico; DFO – Department of Fisheries and Oceans Canada; NMFS AFSC – National Marine Fisheries Service, Alaska Fisheries Science Center; SIU – Southern Illinois University; UAF – University of Alaska Fairbanks; UAS – University of Alaska Southeast; UDEC – Universidad de Concepción; UW, Seattle – University of Washington; UW, Laramie – University of Wyoming.

Appendix A4.–Abstracts of symposium presentations (in alphabetical order by author).

### Groundfish diet data in the eastern Bering Sea with focus on *Chionoecetes spp*.

Kerim Aydin
National Marine Fisheries Service, Alaska Fisheries Science Center, Seattle, WA 98115

Data on the diet of groundfish species in the eastern Bering Sea has been collected since the early 1980s by the Alaska Fisheries Science Center. Within this dataset Pacific cod, sculpin, Alaska skate, and Pacific halibut are observed to be frequent predators of snow crab. For Pacific cod the average size of snow crab consumed increases with increasing fork length. Estimates of the biomass of snow crab consumed vary among years from 60,000 to 150,000 tons with variability primarily attributed to the estimated biomass of Pacific cod. Overall, snow crab are a small component (~5%) of the diet of Pacific cod. Limited data are available for some fish species which may be important predators of snow crab making precise estimation of total predation difficult.

### Eastern Bering Sea snow crab fishery data collection

Heather Fitch
Alaska Department of Fish and Game, Commercial Fisheries Division, Dutch Harbor, AK 99692

Fishery management staff in Dutch Harbor, AK, collect retained catch data by obtaining biological data while vessels are delivering catch to processors, interviewing vessel captains for harvest information, and collecting landing data through fish tickets from processing facilities. The information collected by dockside samplers and observer duties include average weights, evaluating deadloss, and biological data from 100 crabs (carapace width, shell condition, sex, species, and legal status) per landing. Because dockside samplers do not stay on vessels for entire deliveries, the retained catch data that they collect is taken from only a small portion of the catch. Dockside samplers also take part in special projects, including assisting in tagging studies. During interviews vessel captains are asked to provide harvest and effort by statistical area, depth and soak time, size and type of pots, lost pots and rail-dumped pots, and dates of fishing operations. With the implementation of rationalization, fishing information collected by dockside samplers has improved considerably. Vessel captains are now required to keep federal logbooks which have made detailed information easier to obtain. Both the reduction in fleet size and slower pace of the fishery has improved fleet relations. Strong efforts have been made to improve standardization between the dockside sampler and observer data collection methods. Fish tickets are submitted by processors electronically and document delivery weights of both live catch and deadloss, the number of crabs based on average weights, harvest apportionment and effort by statistical area, and other information such as exvessel value, fishing dates, and management program. Both dockside sampler and observer interview information is used to edit the harvest apportionment and effort by statistical area and average weights. Fish tickets are edited due to inaccuracy of or imprecision in the statistical area breakdown of harvest and effort provided to the processors by the captains. The number of crab is also edited due to nonstandardized methods of obtaining average weights. Electronic reporting has improved fish ticket data, allowing for immediate access and data quality checks. The fish ticket database enumerates the retained catch data from the fishery that is used in stock assessments, management reports, and is provided for a variety of other purposes.

### The eastern Bering Sea continental shelf bottom trawl survey

Bob Foy, Claire Armistead, Elizabeth Chilton, and Jan Haaga
National Marine Fisheries Service, Alaska Fisheries Science Center, Kodiak Laboratory, Kodiak, AK 99615

Information on the abundance, distribution, and demography of eastern Bering Sea snow crab is collected by the annual National Marine Fisheries Service crab and groundfish trawl survey. Sampling is conducted using a 83-112 Eastern Trawl (34.1 m footrope) for a 30 min. tow near the center of 20 × 20 nm grid cells distributed across the eastern Bering Sea shelf from Bristol Bay in the east to depths of ~200 m at the shelf edge. Higher density sampling occurs at the center and corners of grid cells occurs near St. Matthew Island and the Pribilof Islands locations with high densities of crabs historically. Biological data collected includes carapace width, shell condition, and sex for all crab sampled, and maturity, egg condition, and clutch fullness index for females. The distribution of snow crab varies by life stage with juvenile males and females observed at depth of 50–100 m and large, adult males and adult females at depths of 100–200 m. Estimates of abundance are calculated as the sum of the average catch per unit effort (number of crab/area swept) in two strata defined by high and low sampling density. The eastern Bering Sea snow crab stock is managed in three districts with longitudinal divisions at 166°W and 173°W. The number and distribution of sampled stations within each district are somewhat variable in the earlier years of the trawl survey time series but all tows within a district are included in estimation. Survey coverage has been consistent since 1990. Available data indicate that large male snow crab targeted by the fishery are located within the area covered by the standard survey. The 2010 survey included areas of the northern Bering Sea which are infrequently surveyed. High densities of snow crab, mostly juvenile, were observed in this area. Snow crab are also observed in bottom trawl sampling at depths of 200–400 m on the continental slope with highest densities in the Zhemchug canyon region but biomass estimates are typically insignificant (<1%) compared to those within the standard survey area. Data and specimens are collected during the survey for a variety of special projects on snow crab maturity, disease, ecology, and reproduction.

### Incorporating new snow crab research into snow crab management

Steve Hughes
Bering Sea Fisheries Research Foundation, Bothell, WA 98021
Dave Somerton
National Marine Fisheries Service, Alaska Fisheries Science Center, Seattle, WA 98115

The catch efficiency of the standard survey trawl has been the focus of recent cooperative (industry/government) research conducted in 2009 and 2010. These experiments consisted of side-by-side tows and comparisons of results in discrete geographic locations to estimate the catchability and selectivity of the standard survey for snow crab. Generalized additive modeling was used to incorporate grain size, depth, and sex as variables in estimation net selectivity function from data collected in 2010. These results indicate increasing selectivity for females with increasing size from 30 to 50 mm after which selectivity is approximately level from 50 to 70 mm. In contrast, selectivity for males increases gradually from 0.2 to 0.3 from 40 to 100 mm and then rises sharply to ~0.80 at 120 mm CW. These results indicate much lower selectivity than experiments conducted in 1999 and indicate that the survey net catches crab with lower efficiency (~20–50%) than the *Nephrops* trawl used for comparisons. Incorporation of these results in the snow crab stock assessment is a priority issue.

### Demography, diet, and reproductive status of snow crab in the northern Bering Sea

Jason Kolts

University of Wyoming, Department of Zoology and Physiology, Laramie, WY 82071

The center of abundance for mature female snow crabs and males of marketable size has shifted to the northwest, away from historical fishing areas in the southeastern Bering Sea. Although NOAA surveyed stations in the Northern Bering Sea Research Area in 2010, very few data exist for snow crabs between St. Matthew Island and the Bering Strait. We characterized the density, distribution, size structure, diets, and reproductive status of snow crabs over this large region of the northern Bering Sea, based on trawl data from 2006 and 2007. Snow crabs occurred throughout our study area, although distributions varied among life stages. Juvenile crab were most abundant at our northernmost stations in the Chirikov Basin and at stations just south of the eastern end of St. Lawrence Island, likely due to advection patterns of larvae or postsettlement immature crab. Mature female crabs were essentially absent from stations in the Chirikov Basin, and occurred at highest densities at our southernmost stations south of St. Lawrence Island. Mature males were found at low densities at stations throughout our study area. Distributions of mature crabs appear to result from migrations of crabs both before and after reaching maturity. Stomach contents indicated a diverse diet for snow crabs of all sizes in all parts of our study area. Immature crabs (<20 mm carapace width) focused on softer, more easily manipulated prey such as amphipods and small bivalves with thin or incompletely calcified shells. Larger crabs consumed larger prey such as harder-shelled bivalves and gastropods that require greater handling ability and claw strength. Most mature females collected were primiparous, bearing a clutch of bright orange, uneyed eggs. Multiparous females were uncommon in our study area, as were old-shell mature males, likely due to a southwestward, ontogenetic migration by crabs of both sexes. Clutch size increased dramatically with carapace width, and was generally higher in multiparous than in primiparous females of the same carapace width interval. The small size attained by mature female crabs in our study area, and their biennial reproductive schedule, greatly reduce their fecundity compared to larger females in the south. Adolescent males south of St. Lawrence Island are likely important for reproduction by primiparous females due to low numbers of adult males.

### 2009 ADF&G Crab Observer Program data collection: sampling design and sources of uncertainty

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I will describe the two-stage probability sampling design underlying ADF&G onboard observer pot lift sampling in the Bering Sea snow crab fishery, summarize 2009/10 sampling effort, and present the methods used to estimate some basic fishery parameters.

**Advancements in understanding life history and spatial processes for eastern Bering Sea snow crab**

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Below we summarize a conceptual model of snow crab life history in the eastern Bering Sea (EBS) which has taken shape over the last decade. Virtually every statement can be recast in the form of a specific hypothesis.

***Habitat***

In the EBS there is close correspondence between the spatial dynamics of the snow crab population and some geographical/hydrographical features. The EBS can be naturally partitioned into bathymetrically defined domains: Coastal (CD), Middle (MD), Outer (OD), and latitudinal sections (NW, Central, SE). Cold near-bottom water (the so called *cold pool*, with near bottom temperature < 2ºC) expands and contracts from year to year along the main axis of the Middle Domain; cold and warm periods have alternated in recent decades, but the pattern of near bottom temperature (NBT) gradients is rather conservative. Predominant direction of residual currents is from SE to NW.

***Life history***

Larvae are in the plankton during the spring and summer. While there is good indication that settlement occurs during late summer and early fall, this event remains poorly documented. Habitat of juveniles is largely circumscribed to the MD, where they settle, grow and recruit to the adult population (i.e., undergo terminal molt). Habitat specificity may be related to the stenothermy and relative cryophyly of early juvenile instars. Molting frequency during early ontogeny is presumably temperature-dependent, but size-at-instar is very conservative across the geographical range of distribution of the species. There is no evidence of skip molting of juvenile females, which start maturing at an age of ~4.5 years postsettlement. There is a latitudinal gradient in the primipara size at adulthood (larger at lower latitudes). Female members of a year class, at a given location, molt to maturity over a period of 4 years and, correspondingly, may reach maturity over a range of 4 instars. Regionally, mature females may belong to (at least) Instars VIII–XII. Larger members of a year class appear to molt first, while small members continue molting. Molting rate into maturity creates an illusory form of density-dependent growth. At the regional scale fast growers get bigger, while at the local scale fastest growers end up being the smallest.

Female terminal molt and primiparous mating occurs during the winter (February–March), while male terminal molt peaks during the summer (June–July). After terminal molt crab migrate offshore (i.e., towards the OD). Female ontogenetic migration appears to follow a predominantly NE to SW direction (at least in the NW and Central sections of the shelf), presumably tracking NBT gradients. Males migrate during the fall, apparently with a N-to-S direction, and by winter large *clean shells* become available to the fishery in the OD. Egg hatching and multiparous mating occurs during the spring (peaking April–May). Maximum lifetime after terminal molt is approximately 7 years, which results in a maximum female longevity of 11.5–14.5 years.

***Potential Larval Dispersal and Connectivity***

Explorations with a coupled biophysical model (output from ROMs and an IBM) indicate that, as expected, there is negligible retention of virtual larvae released in the OD. There is substantial northwestward transport along the MD and westward transport from the MD to the OD, and consistent onshore transport from the OD to the MD, particularly around the Pribilof Islands. Retention of virtual larvae is maximal in the MD, particularly east of the Pribilof Islands. There is transport from the core region to the CD, the Gulf of Anadyr, subarctic regions north of St. Lawrence Island, and even into the Chukchi Sea, but virtually no offshore transport (towards the open Bering Sea) or southward transport throughout the entire geographic region of interest.

***Recruitment and trends in abundance—Females***

Landings of snow crab from the EBS have declined from a maximum of nearly 150,000 mt in 1991 to historical lows on the order of 12,000 mt by 2000. Trends in recruitment and abundance can also be tracked in the female component of the population, which is not harvested and offers the advantage that pseudocohorts of mature females constitute an identifiable life history stage. The geographic range of the snow crab spawning female stock contracted dramatically to the northwest, while pseudocohort strength cycled regularly with a period of approximately 7 years and declining amplitude. The period of the cycle matches time between egg extrusion by a female and peak of terminal molting of her female progeny. Cyclical variation may have been maintained by serial linkage of successive pulses of pseudocohort strength, each of them being the parental stock of the subsequent. The cycle drives trends in Shell Condition Index and Clutch Fullness Index.

The geographical contraction of the reproductive female stock has been addressed by the Environmental Ratchet Hypothesis, claiming that the contraction resulted from a combination of circulation patterns, the spatial dynamics of benthic stages in relation to near bottom temperature, and cod predation. Warm periods result in a northward shift in recruitment to the benthic population (settlement + early benthic survival). There are two possible reasons: (1) appropriate conditions for larval growth and survival are associated with spring blooms that develop under colder conditions; and (2) early juvenile stages are stenothermic, requiring a NBT below 2°C. Once the reproductive stock contracts to the north, re-expansion to the south tracking year-to-year fluctuations in NBT is made difficult because of the northward direction of residual currents. Repopulation of depleted regions may be difficult because routes of ontogenetic migration channel females toward the Outer Domain, whether years are cold or warm.

Fish (prominently cod) predation is a major source of mortality of juvenile stages. Cod prey mostly on Instars iii-vii, settled 1–4 years earlier. After contraction of the stock to the north, cod predation may control the southward expansion of the range of juvenile females. Pseudocohort strength, however, is established early in life history, before females become vulnerable to cod predation. Cod predation appears to track the cycle of recruitment in time and space and may contribute to the environmental ratchet effect, but does not appear to control the cyclic pattern of recruitment.

***Males***

Male recruitment to the mature (adolescent + adult) population (best revealed by the relative abundance of size defined strata) closely matches the cycle of female pseudocohort recruitment, and is reflected by pulses in the fishery. Adolescents and adults appear to be spatially segregated in a way that matches the separation of the primipara and multipara. This opens the possibility of the primipara being fertilized primarily by adolescent males, and the multipara by adult males, which would correspond to Somerton's *Bipartite Mating Hypothesis* on a grand geographical scale. However, it is still uncertain whether the large adult males return to the MD after their post-terminal molt offshore migration to the OD.

***Three puzzling but plausible corollaries***

The conceptual model of EBS snow crab life history and spatial dynamics outlined above suggests three intriguing but plausible implications:

1. Ecological: Snow crab from the EBS may be a contingently quasi-semelparous population, the primipara being the primary contributors to stock renewal.
2. Evolutionary: Some aspects of life-history appear maladaptive for the EBS (e.g., larval release in the OD), perhaps a result of a rigid life history program that succeeds in a variety of subarctic ecosystems, albeit for different reasons
3. Management: The fishery may depend on a segment of the stock (large adult males) whose contribution to renewal of the stock could be relatively small.

## Overview of the eastern Bering Sea snow crab stock

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The eastern Bering Sea snow crab stock is managed with sex (male-only) and minimum-size (3.1″ legal, 4″ industry preference minimum size) harvest regulation and the fishery occurs in the winter and spring. The fishery was declared overfished in 1999 after a dramatic decline in abundance, rationalized in 2005/06, and remains under a rebuilding plan. Harvest rates prior to 1999 were set at 58% but were since reduced and have ranged from 25% to 40% since 1999. The spatial distribution of harvest is small compared to the distribution of legal-sized males observed during the summer fishery leading to questions of local exploitation rate and seasonal movements of males. During the peak harvest years of the 1990s, a high proportion of the catch came from areas to the southwest of the Pribilof Islands a pattern that was not observed during periods of low catches. The Fishery Management Plan (FMP) for Bering Seas/Aleutian Islands king and Tanner crabs established a cooperative state/federal management regime with management deferred to the State of Alaska with federal oversight subject to the FMP and applicable federal laws. Under the authority of this plan the National Marine Fisheries Service (NMFS) under regulations approved by the North Pacific Fishery Management Council and its associated advisory bodies makes decisions on stock status, rebuilding, overfishing, and fishery access. Analogous to this structure the Alaska Department of Fish and Game under regulations approved by the Alaska Board of Fisheries sets the total allowable catch, size, season, gear, and collects fishery data. NMFS conducts the stock assessment survey for snow crab and the two agencies conduct independent and cooperative research on the stock. Research on snow crab has increased substantially in recent years with the decline of the stock. These efforts encompass efforts to improve abundance estimation and stock assessment and advance understanding of spatial dynamics, reproduction, and metapopulation structure.

## Management of the eastern Bering Sea snow crab fishery

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Management of the eastern Bering Sea snow crab fishery is guided by the policies of the Alaska Board of Fisheries which prioritize conservation of reproductive potential and use "…for the greatest overall benefit of the state and the nation." Management must also be consistent with the National Standards of the Magnuson-Stevens Act which include avoiding overfishing, use of the best scientific information, and minimizing bycatch. Measures designed to prevent overfishing include establishing a threshold minimum stock biomass for fishery opening and an overfishing limit (OFL) control rule which establishes a maximum for fishing mortality (including bycatch) which varies as a function of estimated mature male biomass relative to the biomass at maximum sustainable yield ($B_{msy}$). The State of Alaska implements harvest strategies which set the total allowable catch (TAC) with a threshold stock size for fishery opening, an exploitation rate of mature males that scaled to the estimated abundance, and a maximum harvest rate of legal-sized males. Setting the TAC is an annual process which occurs after the OFL level is determined in the stock assessment and reviewed by the Crab Plan Team and Scientific and Statistical Committee of North Pacific Fishery Management Council. Numerous sources of uncertainty are inherent in the stock assessment and TAC setting process. Uncertainties associated with stock characteristics include the size/shell condition distribution, abundance, and distribution. There is also uncertainly in the size/shell condition distribution of landed crab, bycatch mortality rates in the fishery, the relationship between harvest and male and female reproduction, and local exploitation rates. Finally, there is also uncertainty in survey selectivity, natural mortality, handling/discard mortality and additional parameters that are fixed or estimated in the stock synthesis model.

## Stock assessment of eastern Bering Sea snow crab

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A stock synthesis model which integrates population dynamics and fishery information is used for the eastern Bering Sea snow crab stock assessment. The model tracks crab by size, sex, and shell condition classes integrating data on recruitment, growth, maturation, natural mortality, and fishing related mortality (landings and bycatch). Data on the size/sex/shell composition of the stock, bycatch, and retained catch are obtained from the trawl survey (stock), fishery observers (bycatch), and from fishery observers/dockside sampling (retained catch). Adjustments for net selectivity are made by sex and size class using the results of recent net selectivity experiments conducted by the Bering Sea Fisheries Research Foundation and the National Marine Fisheries Service. Outputs from the model are used to estimate $B_{msy}$ and the associated $F_{msy}$ which are then applied to estimate the overfishing limit reference point for the stock. Improved information on growth, aging, the egg production/mature male biomass relationship, and spatial structure including possible localized depletion are priority research items that would better inform the stock assessment.

**Insights from snow crab research and management in the Northwest Atlantic**

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This presentation highlighted some recently published or conducted snow crab research from the Northwest (NW) Atlantic, focusing on growth and recruitment variability and their implications for population reproduction and commercial productivity. As an introductory note, the geographic distribution of snow crab in the NW Atlantic was briefly reviewed and prime habitat was described as consisting of soft bottom areas bathed by the cold intermediate layer (CIL). The core temperature of the CIL varies geographically, with some areas continuously subjected to subzero temperatures and other areas subjected seasonally to temperatures between 1.5°C and 2°C. Moreover, all areas have experienced interannual variability of core CIL temperature, the decade after 1990 being particularly cold.

Field studies in Greenland and the Gulf of Saint Lawrence (GSL) indicate that female and male size-at-terminal molt is directly related to temperature, consistent with observations for females in the Bering Sea. Such variability of size-at-terminal molt is hypothesized to result from the interaction of an age-dependent reaction norm and temperature-dependent growth (warmer-faster) during the early life-history stages (first 2–3 years postsettlement). Differences in growth rate of early juveniles were inferred to result primarily from changes in intermolt period, not molt increment, and this was confirmed through multiple laboratory experiments at controlled temperatures of –1.5°C to 6°C. Although growth rates varied considerably over this spread of temperatures, the range of growth rates realized in nature may be less given the demonstrated narrow thermal preferenda of early juveniles. Changes in juvenile growth rate and size-at-terminal-molt have wide-ranging implications for population reproductive potential, may condition the time elapsed between settlement and recruitment to the fishery, and determine the size of crabs available to the fishery. Evidence was reviewed suggesting that one snow crab population in the GSL was driven to near commercial extinction because of sustained, very cold temperatures that have resulted in most males undergoing terminal molt to sublegal sizes.

Long-term monitoring programs in eastern Canada have shown that recruitment to snow crab populations is episodic, possibly even cyclic, with populations alternating multiyear groups of weak and of strong year classes. The strength of a year class is established very soon in ontogeny and may be related mainly to abiotic and intrinsic population factors that determine numbers of larvae and early juveniles by modulating their production and survival. The mean size of crabs after terminal molt tends to decrease during recruitment pulses and to increase between recruitment pulses, although the underlying mechanisms are not yet perfectly clear. Fluctuating recruitment also determines huge swings in biomass available to the fishery and in adult sex ratio, which condition primiparous female mating success as measured by quantity of accumulated sperm.

Promising areas for future research include (1) further exploration of the reaction norm and thermal control of growth, along with other factors (density, rank of cohort in a recruitment pulse, genetics heritability) that may also contribute to determine size-at-terminal molt; (2) control of year class strength (e.g., climate, cannibalism competition, female spawning biomass); (3) role of groundfish predation in dampening recruitment pulses; (4) existence and importance of female mate choice (overt and cryptic) in the context of fluctuating phenotype and abundance of potential mates; and (5) development of models for understanding population dynamics and testing harvest strategies.

**Bering Sea snow crab data collection in Alaska's Crab Observer Program**

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The State of Alaska Crab Observer Program was established in 1988 to collect essential biological and fisheries data for management of Bering Sea and Aleutian Islands commercial crab fisheries. The program is tasked with supervision, instruction, advisement, and evaluation of onboard crab observer data collection. Required observer coverage in the Bering Sea snow crab fishery is set at 100% for processing vessels and 30% for catcher vessels. Observers live and work onboard commercial snow crab fishing vessels to sample target crab species and bycatch brought onboard in crab pots. Pots to be sampled are randomly selected. Sample selections are spread throughout each fishing day. Vessel operators are interviewed for daily fishing information. Observers also sample retained catch for size and shell condition, average weight, and regulatory compliance. Observers are required to identify and record *Chionoecetes bairdi/C. opilio* hybrid crab encountered in their samples. At-sea winter conditions on the Bering Sea are particularly challenging for data collection. Crab observers conduct special project data and specimen collections opportunistically when time is available. Special project requests should be submitted to the Alaska Department of Fish and Game crab observer program in Dutch Harbor by late March to be considered for the next season.

**Sperm reserves and growth of eastern Bering Sea snow crab (*Chionoecetes opilio*)**

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Snow crab (*Chionoecetes opilio*) support a commercially important fishery in the eastern Bering Sea (EBS), where males of a minimum legal size are harvested. Female snow crab possess sperm storage organs, and if they receive sufficient sperm reserves during mating, they can produce fertilized egg clutches over multiple reproductive cycles. A long-term study was initiated in 2005 to better understand the role female sperm reserves may play in this stock. Spermathecal load (SL) of 831 primiparous snow crab collected between 2005 and 2010 and processed for sperm reserves ranged from 0 to 0.5600 g and averaged 0.0415 g. Significant relationships were detected between SL and female size, year, and area of collection (as defined in three regions), as well as interactions among these factors. The highest levels of SL were observed in the southeast area and the lowest levels were observed in the northwest area. The majority (92%) of primiparous snow crab from the EBS had sperm reserves of less than 0.1 g SL, which is low in comparison to levels reported from snow crab in the Northwest Atlantic. Though evaluation of egg viability indicated most crab in our study received sufficient sperm to fully fertilize their first clutch, levels indicate many would need to re-mate to produce subsequent fertilized egg clutches. Differences observed in SL between spatial regions underscore the importance of understanding how spatial processes affect snow crab in the EBS.

Adolescent male and prepubescent or pubescent female snow crab were collected from the eastern Bering Sea during summer and/or fall stock assessment surveys in 2007–2010 and transported to Kodiak. Crab were held in chilled flow-through seawater tanks (to ~3$^{o}$C) and fed *ad libitim* twice weekly until the occurrence of molting, death, or visible symptoms of possible infection with bitter crab disease. Though lab mortality rates were high, due to a long duration of holding until crab molted (up to 8.5 months) and high incidence of possible infection with bitter crab disease in some years, we achieved growth measurements for 12 males and 45 females to date. Molting occurred between mid-January and mid-May, and is currently ongoing for crab collected in 2010. Preliminary analysis revealed differing trends between the sexes in terms of crab undergoing the terminal molt to adulthood, where growth appeared similar for male snow crab undergoing either an adolescent or terminal molt, but was lower for female snow crab undergoing a terminal molt than either a prepubescent or pubescent molt.

**Seasonal movement of mature male snow crab**

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Understanding patterns of seasonal movements for mature male snow crab in the eastern Bering Sea is crucial to estimating local exploitation rates and variables important to mating and reproductive success. A study with this objective was initiated in the spring of 2011 with the capture and release of 150 mature male snow crab with archival temperature/depth tags. Eleven of these tags were recovered in 2010/11 snow crab fishery. Tidal signals are apparent in the data recovered from the first few tags. Maximum likelihood methods can match the observed tidal signals with those predicted for different locations in the eastern Bering Sea and to infer changes in location between the points of release and recapture. This method was used successfully for rock sole in the Gulf of Alaska. This is an ongoing study with further tag releases planned in the spring of 2011.

**Overview of management strategy evaluation for the eastern Bering Sea snow crab**

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A framework has been created to simulate the management system (i.e., data collection, the stock assessment method, and the decision rules used to calculate OFLs) for snow crab in the eastern Bering Sea. This framework will be used to provide (1) an assessment of the estimation ability of the stock assessment method when all of the assumptions about key processes (e.g., natural mortality, growth, and selectivity) are correct; (2) an evaluation of the estimation ability when assumptions about key processes are violated; and (3) a comparison of different management strategies under recruitment regimes projected 50 years into the future using International Panel on Climate Change climate scenarios. Preliminary results suggest that when the assumptions of the stock assessment are true, quantities used in management are reasonably well estimated. However, when assumptions are violated, biases and loss of precision can be large. For example, incorporating uncertainty associated with small sample sizes used to specify the size-transition matrix nearly doubles the probability intervals for estimated overfishing levels (OFLs). Additionally, using assumptions about natural mortality that are biased by 15% result in OFLs biased by 12%. The results of this study may be valuable in determining future research priorities.

## Reproductive physiology of eastern Bering Sea snow crab (*Chionoecetes opilio*) with a focus on males

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Reproductive cycles of male and female snow crabs are under hormonal control and coordinated to ensure optimal sperm transfer to females prior to egg extrusion. Adolescent females will mate with males directly after their terminal molt, extrude and fertilize their eggs with sperm recently retained in the spermathecae. Primiparous females will incubate embryos for approximately a year after which the embryos hatch and females are ready to reproduce again. As multiparous females, they may mate or utilize stored sperm. Male snow crabs undergo a terminal molt after which it is not clear if they are available to mate with multiparous females. Prior to their terminal molt it is not clear whether males are physiologically capable of transferring sufficient sperm to females. The gonadosomatic index (GSI) of new- and old-shelled males over a broad range of carapace widths (CW) was measured. Male GSI was significantly greater in old-shelled adult and adolescent males when compared to new-shelled adult or new-shelled adolescent males (ANOVA, $P < 0.001$). In both new- and old-shelled males there was a decrease in GSI that was correlated with an increase in CW, but the decrease was not as pronounced in the new-shelled males. It is possible that the decrease in GSI with increasing CW was the result of prior mating history. New-shelled crabs have most recently molted and molting physiology may preclude complete gonad maturation and successful reproductive behavior. Hormones associated with molting (ecdysteroids) and reproduction and behavior (methyl farnesoate) are currently being measured in adolescent and adult snow crabs to determine how the physiology of molting and reproduction is coordinated. Although we know a lot about the temporal patterns of snow crab reproduction we are lacking fine scale spatial information that would clarify the proximity of newly molted adult males to the multiparous female populations.

## Estimating handling mortality in the snow crab fishery

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Management of the eastern Bering Sea snow crab fishery under the Magnuson-Stevens Fishery act requires consideration of the mortality of discarded catch and bycatch in calculations of total fishing mortality. Previous lab and field studies measuring handling and bycatch mortality under various environmental, injury, and gear type scenarios estimated mortality for snow crab to range from 25% to 100%. For management purposes, mortality rates for snow crab are assumed to be 50% for handling mortality in the directed fishery, while bycatch mortality rates are 80% in the trawl fishery, 40% in the dredge fishery, and 20% in the fixed gear fishery. For snow crab most bycatch (~8 million lbs. in 2009/10) was taken in fixed gear (pot) fisheries. A field study using the RAMP (reflex action mortality predictor) which evaluates the probability of crab mortality based on the presence or absence of standardized reflexive responses was initiated in 2010 to improve estimates of handling mortality in the directed fishery. Research biologists collected RAMP scores, sorting time, wind speed, and temperatures data on four fishing vessels while fishery observers collected RAMP data on 18 additional vessels. Predicted mortality rates increased with decreasing temperature below ~5°C. Increased samples sizes are needed in the range of colder temperatures to evaluate interactions between sorting time and wind chill on predicted mortality rates. Temperatures observed aboard fishing vessels tracked well with temperature data from ocean weather buoys indicating that these records from these locations may be useful for index of conditions. Further data will be collected aboard fishing vessels in 2011 to meet refined study objectives. Forecasting mortality rates in advance of the fishing season would be difficult given the need to assume or predict environmental conditions and the fleet fishing schedule.

**Variability in reproductive potential of eastern Bering Sea snow crab, *Chionoecetes opilio*, in relation to spawning stock demography and temperature**

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Biomass-based reference points currently used in management of eastern Bering Sea snow crab, *Chionoecetes opilio*, may be insensitive to demographic variability, resulting in variation in the annual production of viable embryos. To develop improved indices of reproductive potential, we measured fecundity of mature female snow crab collected during the eastern Bering Sea bottom trawl surveys from 2007 to 2009. Snow crab fecundity differed significantly between primiparous (brooding first egg clutch) and multiparous (brooding second or subsequent egg clutch) females. Among multiparous females, fecundity decreased with increasing age, as inferred from shell condition. We developed an index of egg production that incorporates differences in fecundity with shell condition, the estimated proportion of mature females on a biennial cycle of embryo incubation (< 0°C), and the observed proportion of females without egg clutches from bottom trawl survey data from 1978 to 2008. Stock demography (shell condition structure) fluctuated temporally with year class strength as abundant cohorts aged through the mature female population. Primiparous and young multiparous females represented a high mean proportion (81%) of total mature female abundance. Primiparous females were more frequently observed at bottom temperatures <0°C than multiparous females, inferring a higher likelihood of biennial egg production for primiparous females. Incorporating these factors into the egg production index demonstrated decreased stock reproductive potential from 1993 to 1998 and from 2003 to 2008, primarily due to an increased proportion of primiparous and young multiparous females on a biennial reproductive cycle.